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# METHOD AND APPARATUS FOR CHARACTERIZATION OF THERMAL RESPONSE OF GMR SENSORS IN MAGNETIC HEADS FOR DISK DRIVES

## RELATED APPLICATIONS

The present application is related to commonly assigned and co-pending U.S. Patent Application Serial Nos. _________, Attorney Docket No. AUS9-2000-0353-US1 entitled "Method and Apparatus for Measuring Thermal and Electrical Properties of Thermoelectric Materials," ________, Attorney Docket No. AUS9-2000-0354-US1 entitled "Probe Apparatus and Method for Measuring Thermoelectric Properties of Materials," both filed on _______ and both hereby incorporated by reference.

## BACKGROUND OF THE INVENTION

### 1. Technical Field:

The present invention is directed to a method and apparatus for characterization of a thermal response of giant magnetoresistive (GMR) sensors in magnetic heads for disk drives.

### 2. Description of Related Art:

The requirement of high density magnetic storage of data on hard disk drives has been increasing steadily for the past several years. Hard disk drives include magnetic heads for reading and writing data to the hard disk. The magnetic heads include write coils and sensors for reading data from the disks.

Development of magnetoresistive (MR) sensors (also referred to as heads) for disk drives in the early 1990's allowed disk drive products to maximize storage capacity with a minimum number of components (heads and disks). Fewer components result in lower storage costs, higher reliability, and lower power requirements for the hared disk drives.

MR sensors are used for the read element of a read/write head on a high-density magnetic disk. MR sensors read magnetically encoded information from the magnetic medium of the disk by detecting magnetic flux stored in the magnetic medium of the disk. As storage capacity of disk drives has increased, the storage bit has gotten smaller and its magnetic field has correspondingly become weaker. MR heads are more sensitive to weaker magnetic fields than are the inductive read coils used in earlier disk drives. Thus, there has been a move away from inductive read coils to MR sensors for use in disk drives.

During operation of the hard disk drive, sense current is passed through the MR element of the sensor causing a voltage drop. The magnitude of the voltage drop is a function of the resistance of the MR element. Resistance of the MR element varies in the presence of a magnetic field. Therefore, as the magnitude of the magnetic field flux passing through the MR element varies, the voltage across the MR element also varies. Differences in the magnitude of the magnetic flux entering the MR sensor can be detected by monitoring the voltage across the MR element.

As discussed above, MR sensors are known to be useful in reading data with a sensitivity exceeding that

of inductive or other thin film sensors. However, the development of Giant Magnetoresistive (GMR) sensors (also referred to as GMR head chips) has greatly increased the sensitivity and the ability to read densely packed data. Thus, although the storage density for MR disks is expected to eventually reach 5 gigabits per square inch of surface disk drive (Gbits/sq.in.), the storage density of GMR disks is expected to exceed 100 Gbits/sq.in.

The GMR effect utilizes a spacer layer of a non-magnetic metal between two magnetic metals. The non-magnetic metal is chosen to ensure that coupling between magnetic layers is weak. GMR disk drive sensors (or head chips) operate at low magnetic layers. When the magnetic alignment of the magnetic layers is parallel, the overall resistance is relatively low. When the magnetic alignment of the layers is anti-parallel, the overall resistance is relatively high. *When the sensor is biased with a constant current source, the change in resistance results in a change of voltage ("signal voltage") across the GMR sensor. For a given GMR technology, the signal voltage is proportional to the amount of current passed through the GMR sensor. The* current passing through the GMR sensor affects the temperature of the GMR sensor and thus, the thermal noise *voltages. Large currents result in significant temperature change, and a large increase in the noise voltages. As* the temperature increases, the *ratio of signal voltage to noise voltage* is reduced. Th*is* signal to noise ratio *determines* the bandwidth achievable by the GMR sensor.

Because GMR sensors allow extremely high data densities on disk drives, a stable sensor is essential to

accurate read and write operations in high track density hard disk drives. It is known that temperature increases may cause the GMR sensor within the GMR element to exhibit unstable magnetic properties and efforts to reduce the temperature within the disk drive are ongoing.

As the requirements for the GMR sensors have been increasing over the years, the requirements for the write coils within the disk drives have also been increasing. New disk drives require fast field reversal during the write operation. This requirement for fast field reversal during the write operation implies larger write currents for gigahertz operation. Also, as the storage densities increase, the media coercivity has to increase to avoid thermal instability and the superparamagnetic limit. This also implies that larger write currents are necessary. However, large write currents increase the Joule heating in the coil such that the coil temperatures are commonly 40 to 80 degrees Celsius above ambient temperatures. However, for optimal operation, the write coils need to be kept near ambient temperatures.

Several passive and active cooling methods have been proposed to reduce the temperatures in the magnetic heads. These methods and designs require accurate determination of the thermal conductivity and/or microscale temperature characterization. The traditional thermal characterization methods cannot be easily extended to microscopic characterization because of increased parasitic losses associated with the magnetic head probes.

Scanning thermal microscopy (SThM) is a promising technique for microscale thermal characterization and has been recently used for this application. Unfortunately,

the SThM methods proposed do not yield accurate temperature profiles. There is a substantial drop in temperature between the probe tip and the GMR/dielectric surface due to interface impedance. Hence it is difficult to calculate the thermal conductivities of these low thermal conductivity thin film materials.

Thus, there is a need for a mechanism by which thermal conductivities of low thermal conductivity thin film materials can be accurately calculated for use in thermal management of magnetic read/write heads.

**SUMMARY OF THE INVENTION**

A method and apparatus for characterization of a thermal response of giant magnetoresistive (GMR) sensors in magnetic read/write heads is provided. The method and apparatus make use of a probe to measure temperatures at a base and a tip of the probe. With the method and apparatus, the temperature of the magnetic shields of the read/write head is reduced to a temperature lower than the probe temperature. A current is then applied to the GMR sensor to increase the temperature at an air bearing surface until the heat flow through the probe is zero. The amount of current applied, the resistance of the GMR sensor, the magnetic shield temperature, and the ambient temperature are used to calculate the thermal conductance of the dielectric material in the read/write head. The thermal conductance is then utilized to estimate the signal to noise ratio of the GMR sensor and thereby determine a maximum bandwidth of the read/write head.

## BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

**Figure 1** depicts a block diagram of a data processing system in which the present invention may be implemented;

**Figure 2** depicts a cut-away, top plan view of a data storage system in accordance with the present invention;

**Figures 3A** and **3B** are exemplary block diagrams illustrating a GMR sensor in a magnetic read/write head;

**Figure 4** is an exemplary diagram illustrating a probe in accordance with the present invention;

**Figure 5** is an exemplary cross-sectional view of the probe in accordance with the present invention;

**Figure 6** is an exemplary circuit diagram illustrating the thermocouples of the probe;

**Figures 7** and **8** are diagrams illustrating two methods of performing the calibration in accordance with the present invention;

**Figure 9** is an exemplary graph of voltage versus temperature at the tip of the probe, the relationship having been obtained from temperature calibration of the probe;

**Figure 10** is an exemplary diagram that illustrates the basic method of heat calibration in accordance with the present invention;

**Figure 11** is an exemplary graph of $\Theta$ versus temperature differential, the relationship having been obtained from heat flow calibration of the probe tip; and

**Figure 12** is an exemplary block diagram illustrating the use of a probe to measure thermal conductance of a dielectric material in a magnetic read/write head; and

**Figure 13** is a graph of $\Theta$ versus current for a magnetic read/write head under test.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

With reference now to the figures, and in particular with reference to **Figure 1**, a block diagram of a data processing system in which the present invention may be implemented is illustrated. Data processing system **100** is an example of a client computer. Data processing system **100** employs a peripheral component interconnect (PCI) local bus architecture. Although the depicted example employs a PCI bus, other bus architectures, such as Micro Channel and ISA, may be used. Processor **102** and main memory **104** are connected to PCI local bus **106** through PCI bridge **108**. PCI bridge **108** may also include an integrated memory controller and cache memory for processor **102**. Additional connections to PCI local bus **106** may be made through direct component interconnection or through add-in boards. In the depicted example, local area network (LAN) adapter **110**, SCSI host bus adapter **112**, and expansion bus interface **114** are connected to PCI local bus **106** by direct component connection. In contrast, audio adapter **116**, graphics adapter **118**, and audio/video adapter (A/V) **119** are connected to PCI local bus **106** by add-in boards inserted into expansion slots. Expansion bus interface **114** provides a connection for a keyboard and mouse adapter **120**, modem **122**, and additional memory **124**. In the depicted example, SCSI host bus adapter **112** provides a connection for hard disk drive **126**, tape drive **128**, CD-ROM drive **130**, and digital video disc read only memory drive (DVD-ROM) **132**. Typical PCI

local bus implementations will support three or four PCI expansion slots or add-in connectors.

An operating system runs on processor **102** and is used to coordinate and provide control of various components within data processing system **100** in **Figure 1**. The operating system may be a commercially available operating system, such as OS/2, which is available from International Business Machines Corporation. "OS/2" is a trademark of International Business Machines Corporation. An object oriented programming system, such as Java, may run in conjunction with the operating system, providing calls to the operating system from Java programs or applications executing on data processing system **100**. Instructions for the operating system, the object-oriented operating system, and applications or programs are located on a storage device, such as hard disk drive **126**, and may be loaded into main memory **104** for execution by processor **102**.

Those of ordinary skill in the art will appreciate that the hardware in **Figure 1** may vary depending on the implementation. For example, other peripheral devices, such as optical disk drives and the like, may be used in addition to or in place of the hardware depicted in **Figure 1**. The depicted example is not meant to imply architectural limitations with respect to the present invention. For example, the processes of the present invention may be applied to multiprocessor data processing systems.

With reference now to **Figure 2**, a cut-away, top plan view of a data storage system is depicted in accordance with the present invention. Data storage system **200** is an example of a data storage system which may be

implemented as a disk drive such as, for example, disk drive **126** in **Figure 1**. Data storage system **200** includes a housing **201** containing at least one rotatable data storage disk **202** supported on a spindle **205** and rotated by a drive motor (not shown). Typically, a data storage system will comprise a plurality of disks and a slider **206** with a read/write head **204** for each disk. As an example, in a magnetic disk storage device, each data storage disk **202** has the capability of receiving and retaining data, through the use of a magnetic recording medium formed on at least one disk surface **203**, where the magnetic recording medium is arranged in an annular pattern of multiple concentric data tracks **208**. Though only a few data tracks **208** are shown, it is known that the number of tracks varies according to at least the recording medium and the read/write head **204**. At least one slider **206**, including one or more read/write heads **204** is positioned over data storage disk **202**. Slider **206** is suspended from an actuator arm (not shown) by a suspension (also not shown) and the radial position of slider **206** with respect to data tracks **208** of data storage disk **202**, is controlled by a voice coil motor (not shown).

During operation of data storage system **200**, the rotation of data storage disk **202** generates an air bearing between slider **206** and disk surface **203**. The air bearing counterbalances a slight downward-biased spring force of the suspension and supports slider **206** above disk surface **203** by a small, substantially constant spacing. As disk **202** is rotated by the drive motor, slider **206** is moved radially in and out in response to

the movement of the actuator arm by the voice coil motor, permitting read/write head **204** to read and write data from and to the concentric tracks **208**. Though only one read/write head **204** and slider **206** assembly is shown, it is well known that a plurality of sliders **206** may be employed to access a plurality of disks **202**, stacked one atop the other on spindle **205**.

The temperature of read/write head **204** may rise during operation of data storage drive **200** due to previously discussed magnetic field changes and ambient conditions in data storage system **200**. During operation, read/write head **204**, passes through magnetic field changes induced by stored data in the magnetic medium of disk **202**. Temperature increases in read/write head **204** may be the result of many different causes including Joule heating of the sensing current, frictional asperities, the magnetic field changes encountered while passing over the surface of disk **202**, and the like. As read/write head **204** passes over magnetically encoded data in the form of bits, the changing magnetic fields encountered by read/write head **204** causes head resistance to change, which generates heat within read/write head **204**. Magnetic instability may arise in read/write head **204** due to increasing read/write head **204** temperatures. Magnetic instability causes noise and, concurrently, distortions in a current flow pattern in an active region (area (not shown) between bias field conductors of read/write head **204**). A thermoelectric cooling (TEC) device, may be mounted in close proximity to read/write head **204** to provide an active heat transfer device. Also, the TEC device may utilize a separate power source

or in very low temperature conditions, the same power source as the read/write head **204**.

**Figures 3A** and **3B** show cross sections of a magnetic head **300** having a giant magnetoresistive (GMR) sensor **310**. As shown in **Figure 3A**, the magnetic head **300** includes a yoke **305**, a GMR sensor **310**, coils **315**, layered dielectrics **320**, and magnetic shields **325**. The magnetic head **300** is positioned above a spinning magnetic disk **330** with a gap **335** allowing for air flow between the magnetic head **300** and the spinning disk **330**. The coils **315** generate a magnetic field for writing data to the spinning disk **330**. The coils **315** are wrapped around yoke **305** which focuses the magnetic field created by the coils **315**. The GMR sensor **310** is used for reading data from the spinning disk **330**. The layered dielectrics **320** are used as an insulator for insulating the GMR sensor **310** from the magnetic shields **325**. The magnetic shields **325** shield the write operations of the coils **315** from the read operations of the GMR sensor **310**.

**Figure 3B** shows a magnified view of the GMR sensor **310** from the air bearing surface (**ABS**), such as represented by arrows **338**. The GMR sensor **310** is positioned between two electrical leads **340**. The GMR sensor **310** is also sandwiched between dielectrics **320** and magnetic shields **325**.

The GMR sensor **310** typically operates at approximately 50 degrees Celsius above the spinning disk ambient temperature. Most temperature drops occur within the GMR sensor **310** layers and the ultra-thin alumina

dielectrics **320** between the GMR sensor **310** and the magnetic shields **325**. The present invention provides a method and apparatus for accurately characterizing the thermal conditions of the GMR sensor **310** at the tip of the magnetic head **300**.

The present invention provides a method and apparatus for measuring and characterizing the thermal and electrical properties of GMR sensors in magnetic read/write heads. The invention makes use of temperature sensors, such as thermocouples and thermistors, for thermal probes and uses a surface electrode at the thermal probe tip for making electrical measurements on a sample of the thermoelectric material.

The preferred embodiment of the present invention makes use of two thermocouples as the temperature sensors of the present invention. However, it should be appreciated that the present invention may use other types of temperatures sensors to measure the temperature values at various points on the probe without departing from the spirit and scope of the present invention. For example, rather than two thermocouples, the present invention may use one or more thermistors in place of or in addition to one or more of the thermocouples of the preferred embodiment. For purposes of illustration, however, the present invention will be described in terms of a probe having two thermocouples which are used to measure temperature.

While the present invention will be described in terms of using a particular type of probe to measure heat flow through the surface of a read/write magnetic head, the invention is not limited to this particular probe design. Rather, any probe that is capable of measuring

heat flow may be used without departing from the spirit and scope of the present invention. The preferred embodiments, however, make use of a probe having the configuration and operational abilities herein described.

**Figure 4** is an exemplary diagram illustrating two views of a probe **400** in accordance with the present invention. The probe shown in **Figure 4** is used to measure the thermoelectric properties of thermoelectric materials in a manner described in detail hereafter. The probe in **Figure 4** makes use of two thermocouples to provide measurements of temperature that are then used to calculate thermoelectric properties of the thermoelectric material sample under test.

As shown in **Figure 4**, the probe **400** includes a cantilever substrate structure **410**, a first lead **420**, a second lead **430**, a third lead **440**, a fourth lead **445**, a reflector **450**, and a cone **460**. The leads **420-445** create two thermocouples which are used, in a manner to be described hereafter, to measure the temperature of the probe tip (cone **460** tip) and the temperature of a sample material. From these measurements, the thermoelectrical properties of the sample material may be determined.

The reflector **450** is used to reflect a laser beam toward a detector (not shown). The laser beam, reflector **450** and detector are used to measure the deflection of the cantilever structure **410** in order to maintain the distance between the probe tip **460** and the sample material at a constant value.

**Figure 5** is an exemplary cross section of the probe tip **460**. As shown in **Figure 5**, the probe tip **460** is comprised of a number of different layers of material.

The particular materials described hereafter with reference to the exemplary embodiment are meant to be for illustrative purposes and other materials having similar properties may be used in replacement or in addition to the materials described herein without departing from the spirit and scope of the present invention.

The formation of the probe tip **460** will now be described with reference to **Figure 5**. The formation of the probe tip **460** is generally described in the incorporated co-pending U.S. Patent Application Serial Nos. __________ (Attorney Docket No. AUS9-2000-0353-US1) and _________ (Attorney Docket No. AUS9-2000-0354-US1). The mechanisms used to create the various layers of the probe, such as deposition and etching, are generally known in the art of semiconductor chip manufacture. However, these mechanisms have not previously been used to create the structure herein described.

The cantilever substrate **410** is created first and is comprised of a silicon or silicon nitride material. A silicon oxide cone **460** is formed on the cantilever substrate **410**. A secondary metal layer is then created over the substrate **410** and the cone **460**. The secondary metal layer may be, for example, chromium, and is used to create the second lead **430** and third lead **440**.

It should be noted that the chromium layer does not cover all of the surface of the substrate **410** and cone **460**. Rather, as shown in **Figure 5**, a portion of the chromium layer at the base of the cone is etched away so that the two leads **430** and **440** are formed without touching one another.

Once the two leads **430** and **440** are created, a silicon oxide layer **480** is created on top of the chromium layer. The silicon oxide layer **480** is etched at the apex of the cone and at a point at the base of the cone to create two thermocouples which will be used in the present invention to perform thermoelectric property measurements of sample materials.

After the silicon oxide layer **480** is created, the primary metal layer **420** is created. The primary metal layer **420** is comprised of platinum/iridium in an exemplary embodiment, but may be any other type of metal which may be determined to have properties especially well suited for a particular application. As shown in **Figure 5**, the primary metal layer **420** is etched away at position near the base of the cone to thereby create the first and fourth leads **420** and **445**.

The interaction of the primary and secondary metal layers at the points where the silicon oxide layer **480** was etched away, creates the thermocouples which are used for measurements of nanoscopic material properties. Additional layers of material may be added to the structure shown in **Figure 5** so long as these additional layers do not interfere with the operation of the dual thermocouples. For example, fine wires may be added to the cantilever structure **410** for heating the cantilever structure to thereby create a temperature differential, as will be described hereafter.

While the probe structure shown in **Figures 4** and **5** show a cone-shaped probe tip, the probe tip may be of any shape desirable. For example, the cone-shaped probe tip may be very narrow or very wide in diameter, may have any

value interior angle at the tip, and the like. However, a narrower tip is preferable since the tip localizes measured temperature fields to a smaller area and thus, makes the probe capable of measuring thermal properties of smaller scale materials.

The probe created using the process described above can be used for making measurements in many different applications. For example, the probe may be used to determined the thermoelectrical characteristics of a GMR sensor read/write head in a disk drive.

Those of ordinary skill in the art will appreciate that the probe of the present invention is utilized along with a computing system, such as, for example, the computing system shown in **Figure 1**, in which the calibration and computations described hereafter are performed. The probe is used to provide measured quantities which are then processed by the computing system to calibrate the probe and generate values for the thermoelectric properties of the materials under test.

Before the probe can be used to measure the thermoelectric properties of sample materials, the probe must be calibrated. The calibration is performed using a sample whose thermoelectric properties are generally known in order to obtain a relationship of thermoelectric properties. The calibration method generally includes the steps of:

1) measuring the voltages across each of the thermocouples;
2) measuring the temperature from a bottom lead to the back side of the sample;
3) calibrating temperature according to NIST standards based on the above measurements; and

4) calibrating heat flow using the known thermoelectrical properties of the sample.

**Figure 6** shows a circuit schematic for a mixed mode operation probe in accordance with the present invention. As shown in **Figure 6**, the probe **400** consists of a first lead **420**, a second lead **430**, a third lead **440** and a fourth lead **445**. The voltage $V_{t1}$ across the first and second leads **420** and **430**, connected to the thermocouple at the tip **460**, are used to monitor the temperature and the heat flow out of the tip of the cone of the probe. The voltage $V_{t2}$ across the third and fourth leads **440** and **445**, connected to the thermocouple at the base, are used to monitor the temperature and the heat flow at the base of the cone of the probe. Based on these voltages, the difference in temperature $\Delta T_t$ between the tip and base of the cone can be calculated. Current-voltage (I-Vs) measurements at the first and fifth leads **420** and **630** characterize the electrical properties of the sample **610**.

The temperature sensors, i.e. thermocouples, at the tip may be calibrated in a number of different ways. In particular, the preferred embodiment of the present invention calibrates the temperature sensors at the tip by scanning the probe tip over a base of a pre-calibrated surface and over a metal surface of a thermoelectric cooler **620** concurrently. For example, the pre-calibrated material may be a platinum base of a pre-calibrated silicon diode mounted on the thermoelectric cooler and the metal surface may be a copper metal surface of the thermoelectric cooler **620**, as shown in **Figure 7**. In

separate calibration, scanning a metal surface of a thermoelectric cooler may be concurrently monitored by a pre-calibrated E-type thermocouple, for example, as shown in **Figure 8**. Regardless of the particular manner by which calibration is performed, the method of temperature calibration is essentially the same.

The temperature sensors, i.e. thermocouples, at the tip and base of the cone **460** are used to measure voltage values for various tip and sample temperatures. With the present invention, a laser, which may be used may be used to detect cantilever deflection of the probe **400**, is switched OFF and the thermoelectric cooler **620** is activated to increase and decrease the temperature of the sample near the ambient.

Measurements of the voltages $V_{t1}$ and $V_{t2}$ are made using the thermocouples and are used to plot a relationship between the voltages and the temperature of the precalibrated surface. Using National Institute of Standards and Technology (NIST) temperature standards, a relationship of voltage to temperature is identified using known points. **Figure 9** shows an exemplary relationship between the tip voltage and the tip temperature. In this way, a one-to-one relation table between the thermocouple sensor voltage $V$ and the temperature $T$ may be obtained.

Although the above method is used in the preferred embodiment of the present invention, other methods of performing temperature calibration may be used with the present invention without departing from the spirit and scope of the present invention.

Once temperature calibration is performed, the thermocouple sensors must be calibrated for measurement

of heat flow. The heat flow calibration makes use of a material having known thermoelectric properties. In particular, materials having known Seebeck coefficient $\alpha$ and thermal conductivity $\lambda_{k,}$ are utilized.

**Figure 10** is an exemplary diagram that illustrates the basic method of heat calibration in accordance with the present invention. The heat flow $Q$ from the tip to the sample surface is calibrated by scanning the probe tip in a contact-mode of operation over thermoelectric materials, such as $Bi_{0.5}Sb_{1.5}Te_3$, $Bi_2Te_{2.9}Se_{0.1}$, ZnSb, and Bi crystals, whose Seebeck coefficient $\alpha_{known}$ and thermal conductivity $\lambda_{known}$ are known. The heat flow balance results in the following equation:

$$Q_p(\Delta T_t) = G\lambda_k\Delta T_s \qquad (1)$$

where $\Delta T_s$ is the temperature drop across the sample and $G$ is a geometric parameter. $G \approx 2\pi a$ where $a$ is the "thermal" radius of the probe tip. The value for $\Delta T_s$ equals the ratio of the voltage across the thermocouple between leads **420** and **440** and the Seebeck coefficient of the material ($V/\alpha$). The open circuit voltage $V_{known}$ is measured across leads **420** and **630**. Thus, the equation becomes:

$$\frac{Q_p(\Delta T_t)}{G} = \lambda_{known}(V_{known}/\alpha_{known}) \qquad (2)$$

As shown in **Figure 11**, the quantity ($Q_p/G$), denoted by $\Theta$, which is sometimes referred to as the normalized heat flow, can be tabulated for standard conditions,

e.g., when the laser used for monitoring deflection is turned OFF (curve a) and turned ON (curve b). $\Theta = 0$ at $T_t = 0$ when the laser is OFF, and at $T_t = \Delta T_1$ when the laser is ON. Thus, from the temperature and heat flow calibrations above, the relationships $V_t/T_t$ and $\Theta/\Delta T_t$ provide a complete thermoelectric calibration and characterization of the probe tip.

After calibration, the probe may be used to thermally characterize the GMR sensor of the read/write head. **Figure 12** shows how the probe apparatus of the present invention is applied to the magnetic head of **Figure 3A** to perform thermal characterization of the GMR sensor at the tip of the magnetic head. The thermal characterization method exploits the $\Theta = 0$ condition at the probe tip to measure the surface temperature. Under this condition, there is no temperature drop across the interface between the probe tip and the read/write magnetic head. The probe tip is used on the air bearing surface of the read/write magnetic head to measure temperatures and determine heat flow through the probe.

In order to obtain the condition $\Theta = 0$ condition at the tip of the probe, the slider backside of the read/write magnetic head is first mounted on a thermoelectric cooler **1210** and the magnetic shields **1220** of the read/write magnetic head are cooled to a temperature $T_b$ less than the ambient temperature $T_a$ ($T_b<T_a$ or $T_b<T_a+\Delta T_1$ if the laser in ON).

The current through the GMR sensor **1230** is then increased so that the air bearing surface (ABS) warms up and a loci of points on the ABS under the magnetic head attains the condition $\Theta = 0$ when $I = I_1$. The heat flux $Q_p$

through the probe tip is zero and $T_t = T_{gmr} = T_a$ (or $T_t = T_{gmr} = T_a + \Delta T_1$ if the laser is ON) on this loci ($T_{gmr}$ is the temperature of the GMR sensor). These contours can be traced for different values of I and $T_b$ and the entire temperature/current behavior can be obtained as shown in **Figure 13**.

In particular, when $\Theta = 0$ at the center of the GMR sensor **1230**, the entire Joule heat at the surface of the GMR sensor is conducted through the dielectric material **1215** to the magnetic shields **1220**. Hence the effective thermal conductance K between the GMR sensor **1230** and the magnetic shields **1220** can be calculated from the relation:

$$K_{eff} = (I_0^2 R_{gmr}) / (T_a - T_b) \qquad (3)$$

Where $K_{eff}$ is the effective thermal conductance, $I_0$ is the current through the GMR sensor, $R_{gmr}$ is the electrical resistance of the GMR sensor which may be determined by measuring the voltage across the GMR sensor, $T_a$ is the ambient temperature, and $T_b$ is a backplane temperature, e.g. the magnetic shield temperature. The above relationship is valid when the temperature of the GMR sensor is substantially the same as the probe tip. However, in many cases the probe tip temperature can be increased by having a heater coil in the probe. In such a case, $T_a$ in the above relationship may be replaced by the probe tip temperature and $T_b$ may be higher than the ambient temperature.

Thus, the thermal conductance of the dielectric material **1215** between the GMR sensor **1230** and the magnetic shields **1220** may be obtained when the current being passed through the GMR sensor **1230** is known, the ambient temperature and the thermoelectric cooler temperature are known, and the thermal resistance of the GMR sensor is known. Based on the thermal conductance, the operational behavior of the GMR sensor may be modeled in order to manage the temperature of the magnetic read/write head. By managing the temperature of the magnetic read/write head, optimal performance of the read/write head may be obtained.

For example, using the thermal conductance determined using the probe mechanism described above, the signal to noise ratio of the GMR sensor may be estimated. As mentioned above, the signal to noise ratio provides a measure of the maximum bandwidth obtainable by the GMR sensor. Based on the maximum bandwidth of the GMR sensor, the read speed of the read/write head can be determined. The maximum bandwidth of the GMR sensor may be determined using the relationship:

$$\Delta f \propto (\Delta R/R)^2/((1/K)+(T_b/P)) \qquad (4)$$

where $\Delta f$ is the bandwidth, $\Delta R$ is a change in the resistance of the GMR sensor, R is the resistance of the GMR sensor, K is the thermal conductance of the GMR sensor, Tb is the backplane or shield temperature, and $P=I^2R=K(T-T_b)$.

Moreover, the thermoelectrical characteristics of the read/write head may be modeled and cooling of the read/write head may be controlled using the model of the

thermoelectric characteristics of the read/write head. Other uses of the measured thermal conductance may be made without departing from the spirit and scope of the present invention.

It is important to note that while the present invention has been described in the context of a probe apparatus coupled to a fully functioning data processing system, those of ordinary skill in the art will appreciate that the processes of the present invention are capable of being distributed in the form of a computer readable medium of instructions and a variety of forms and that the present invention applies equally regardless of the particular type of signal bearing media actually used to carry out the distribution. Examples of computer readable media include recordable-type media, such as a floppy disk, a hard disk drive, a RAM, CD-ROMs, DVD-ROMs, and transmission-type media, such as digital and analog communications links, wired or wireless communications links using transmission forms, such as, for example, radio frequency and light wave transmissions. The computer readable media may take the form of coded formats that are decoded for actual use in a particular data processing system.

The description of the present invention has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. The embodiment was chosen and described in order to best explain the principles of the invention, the practical application, and to enable others of ordinary skill in the art to understand the invention for

various embodiments with various modifications as are suited to the particular use contemplated.